

Laparoscopic Multifunctional Instruments: Design and Testing of Initial Prototypes

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ABSTRACT

Background: Advances in minimally invasive surgical techniques will require new types of instrument end-effectors for smaller, longer, and flexible instruments. These include a new class of multifunctional instruments capable of performing more than 1 task with a single set of working jaws. Furthermore, it is desired that multifunctional instruments be designed to provide improved dexterity compared with that in currently commercially available instruments.

Methods: Three prototypes of multifunctional laparoscopic surgical instruments are described: (1) a mechanical scissors-grasper, (2) a mechanical scissors-grasper-articulator, and (3) a compliant mechanism scissors-grasper. Methods of baseline analysis, design methods and considerations, and subjective evaluations of interim prototypes are presented.

Results: The 3 prototypes demonstrate promising early results. However, based on subjective evaluation, these prototypes do not perform individual functions as well as basic disposable single-function laparoscopic instruments do.

Conclusions: The concept of multifunctionality and increased end-effector dexterity is achievable as demonstrated by the prototypes presented. Further work is required to refine, simplify, and improve the multifunctional instruments to a point where they may be useful as surgical tools.

Key Words: Laparoscopy, Multifunctional laparoscopic instruments.

INTRODUCTION

Most instruments used for minimally invasive surgery (MIS) are single-function by design and are continually exchanged during endoscopic procedures. Instrument exchanges comprise 10% to 30% of total time thus adding to procedure time,¹ disrupting the surgeon's train of thought, and possibly compromising the patient's safety.² Surgeons stand to benefit from the availability of dexterous multifunctional instruments, ie, instruments that are capable of performing more than 1 task with a single set of working jaws.

In 1996, Melzer¹ provided an extensive review of advanced concepts for "intelligent" endoscopic instruments and described several devices that could be considered multifunctional. These included an instrument that could perform blunt dissection as well as suction and irrigation and a tool that combined a high-frequency hook with an ultrasonic dissection probe. Cohn et al³ and Sastry et al⁴ have developed hand-like end-effectors that provide a high level of dexterity, but have limited force output capability. Pietrabissa et al⁵ presented a multifunctional instrument for hand-assisted laparoscopic surgery that exhibits grasping and dissecting capabilities. Other tools include an elastic jaw grasping forceps that utilizes 2 elastic beams in place of a mechanical hinge joint.⁶

Several instrument designs that could be considered multifunctional are reported in patent filings. These devices include a grasping device with an extending articulation feature.⁷ This device, however, placed the articulation pivot far off the tool's axis making it difficult to administer precise movement. Other patents include a compliant grasping tool design with transversely retractable scissor blades,⁸ a surgical instrument comprising a grasping end-effector with a transversely extendable blade along side the end-effector used for cutting in the knee cavity joint operation,⁹ and a handle for a medical instrument that could be used to control a 2-function instrument.¹⁰

Laparoscopic instruments are often used to perform a variety of functions in addition to their primary design function. Based on a prior study, patterns of usage and instrument exchanges in common laparoscopic procedures were identified.² With this background, we focused

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on developing dexterous instruments for MIS that are capable of performing more than 1 task with a single set of working jaws.

METHODS

Three prototype instruments were designed to perform multiple functions at the tool tip using a single set of working jaws with a single handle input to control each function. The combination scissors and grasper was selected as a candidate for multifunctional design, and a 5.0-mm diameter effector and shaft platform was used for the laparoscopic instrument development. One important design consideration applicable to all prototypes is the surface of the working jaws. A compromise was needed between conflicting design requirements of rough grasping surfaces with smooth cutting surfaces.

Prototype #1: Mechanical Scissor-Grasper (Figures 1 and 2)

Figure 1 shows that the intermediate portion of the jaws has a smooth surface with a sharp edge for cutting, and a small portion of the tip and the proximal portion of the working jaws have texture for grasping. The end-effector mechanism is actuated by 2 half-circular cross-section pushrods. The grasping motion of the end-effector is accomplished through a pin and slot mechanism (**Figure 1A**). As the pushrod is moved forward or backward, the pin slides in the slot, causing the grasping jaw to open and close, while the second jaw remains stationary. Cutting is controlled by the second pushrod, linked to the second jaw (**Figure 1B**). As the pushrod is moved, the connecting link causes a rotational motion of the end-effector cutting scissor blade producing a scissors shearing action, while the first jaw remains stationary.

A toggle switch on the top of the handle is moved side to side to switch between cutting and grasping functions

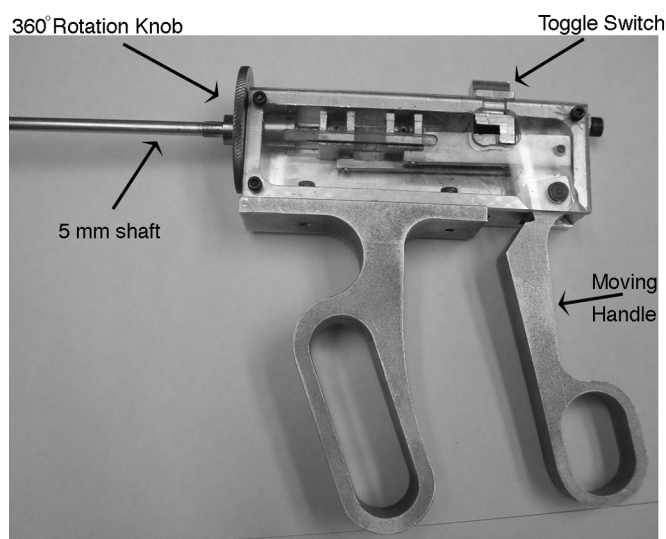


Figure 2. Prototype 1: Mechanical Scissors-Grasper.

(**Figure 2**). The 2-position toggle switch engages one of the pushrods to the input handle while the other pushrod is locked in position. A finger knob on the shaft allows rotation of the instrument shaft 360° about its axis.

Prototype #2: Mechanical Scissors-Grasper-Articulator (Figures 3 and 4)

The multifunctional scissors-grasper-articulator design is similar to the scissors-grasper design, but a third function of articulation is added. The function of articulation permits the jaws to rotate 80° off axis approximately 12 mm from the distal instrument tip (**Figures 3D, 3E**). Articulation is actuated via 4 cables routed through the shaft from the handle to the end-effector. The working grasper jaws articulate by rotating in a plane perpendicular to the plane of opening and closing of the jaws. This articulation provides nonlinear access at the surgical site. When the instrument is in scissors mode, one of the jaws is held

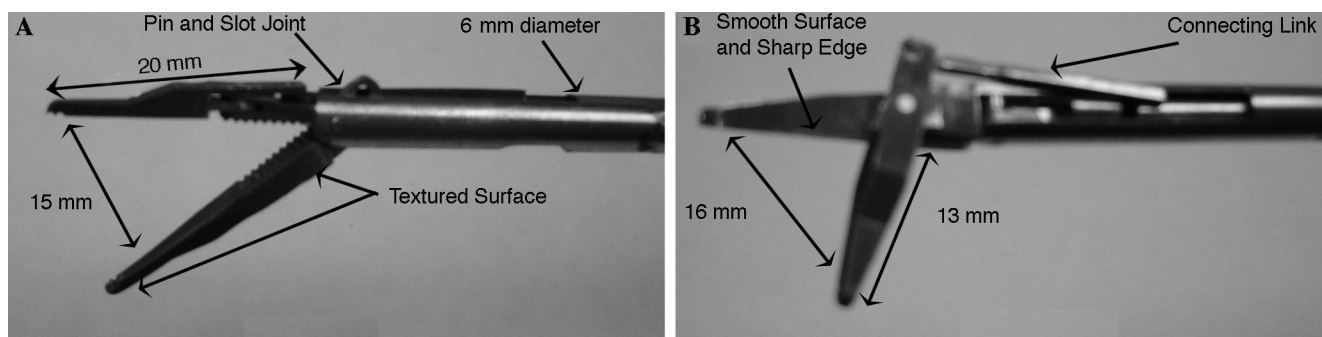


Figure 1. Prototype 1: Scissors-Grasper End Effector. Grasper (A), scissors (B).

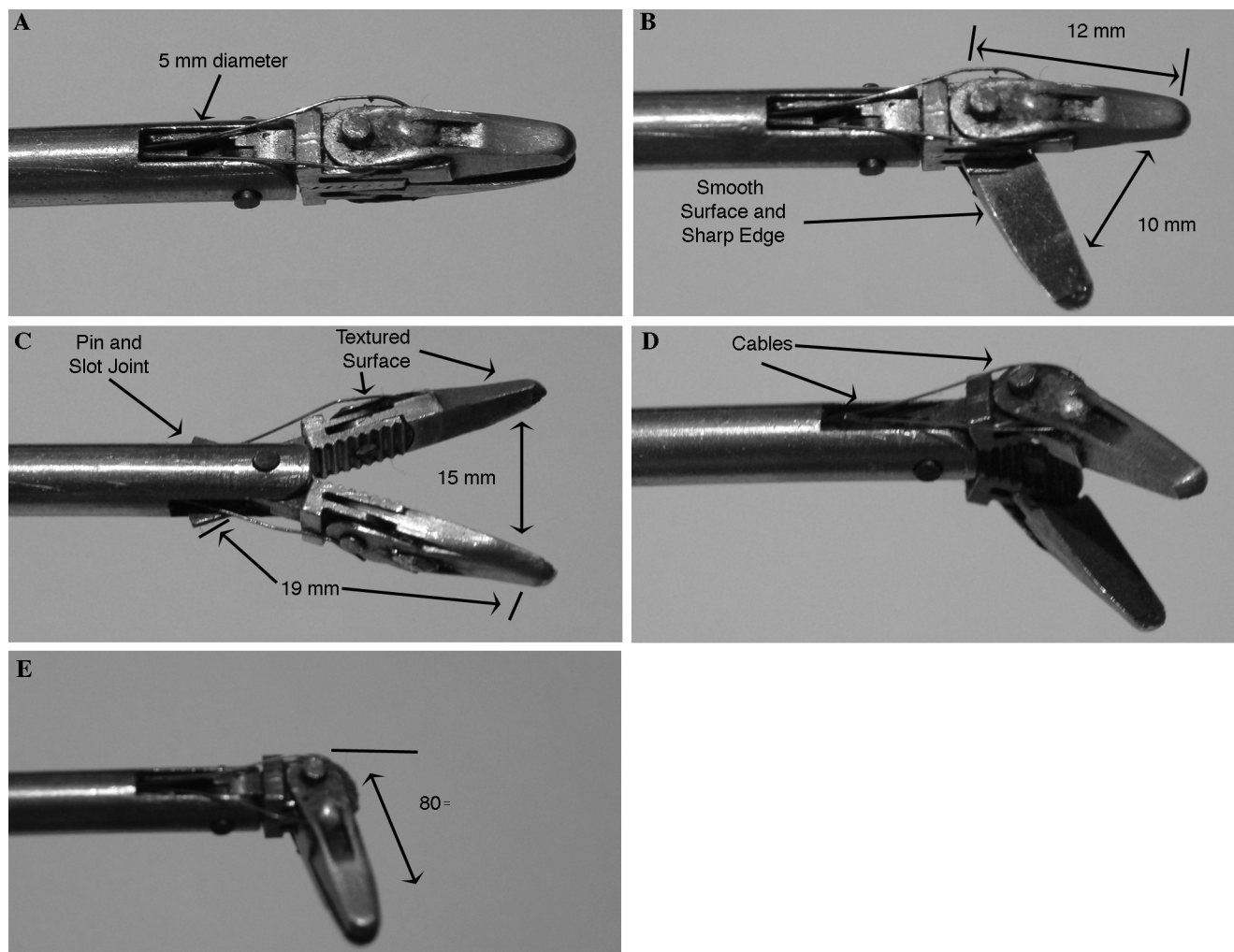


Figure 3. Prototype 2: Scissors-Grasper-Articulator End-Effector. Closed (A), grasper open (B), scissors open (C), closed articulated (D), open articulated (E).

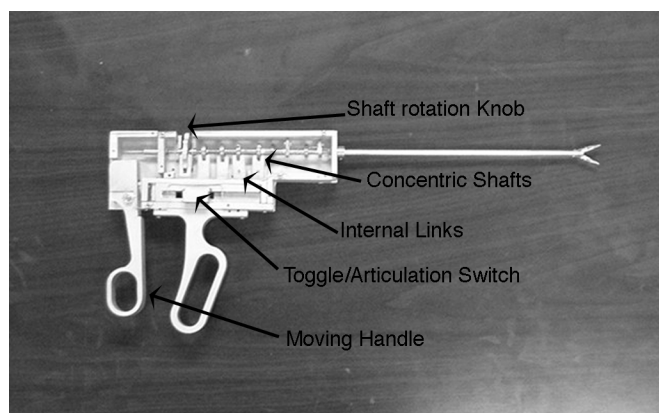


Figure 4. Prototype 2: Mechanical Scissors-Grasper-Articulator.

stationary. When the moving handle link is rotated, 2 steel cables connected to the upper jaw are actuated producing a scissor motion (**Figure 3B**). The grasping motion is activated via a pushrod and pin and slot joints (**Figure 3C**).

Figure 4 shows the articulation switch in the handle, which by sliding forward or backward moves the corresponding internal links connected to the concentric shafts and articulation cables to control both grasper and scissor motions. The mechanical connection between the sliding links and the concentric shafts uncouples the rotational motion of the shaft and the translational motion of the sliding internal links, thus allowing the cables to be actuated at any angular position of the shaft. When moved transversely into and out of the side of the handle, the toggle switch switches the instrument between scissors and grasper modes.

Prototype #3: Compliant Scissors-Grasper

This prototype incorporates a compliant mechanism that is a single-piece flexible structure that exploits elastic deformation to achieve motion transmission. It can be thought of as a mechanism without hinge joints. The topology optimization software used to design and analyze the compliant mechanism structural elements has been previously discussed by Frecker and Dzedzic.^{11,12}

Figure 5 illustrates the prototype compliant end-effector in its 3 primary positions, where the grasping and cutting occur in perpendicular planes. The prototype end-effector was fabricated from stainless spring steel using wire electro-discharge machining and micro-milling. The working portion of the jaws is 12.5-mm long, but the compliant mechanism is 36-mm long to allow the jaws to open completely without overstressing the compliant members.

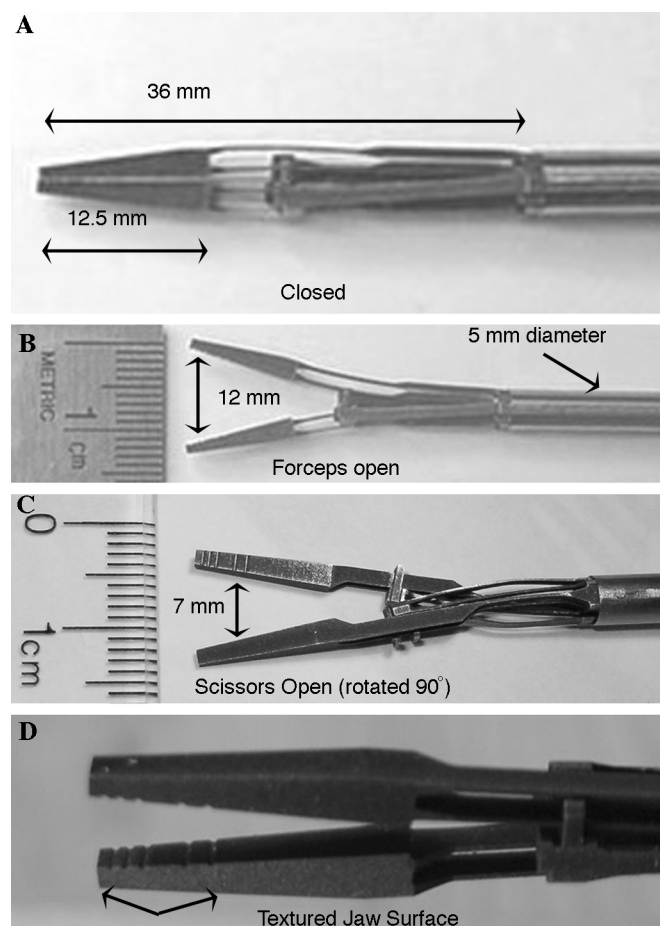


Figure 5. Prototype 3: Compliant Scissors-Grasper End Effector. Closed (A), grasper open (B), scissors open (C), textured jaw surface (D).

The distal portions of the jaws have texture to provide friction during grasping, as shown in **Figure 5D**.

The prototype instrument shown in **Figure 6** has a compliant tool tip actuated by pushrods that connect the handle to the distal end of the instrument. One rod forces the grasping jaws closed by pulling on the outer portion of the tip, and a second rod forces the scissor blades closed by pulling on the inner portion. The compliant mechanism does not have any hinges and works by elastic deformation; therefore, it requires an increasing amount of input force to increase the deflection of the tool tip. A static balance mechanism was added to the handle to counteract this effect and reduce the “stiffness” felt at the handle. The static balance mechanism together with the compliant mechanism has equal potential energy in any position, thus the force required to actuate the system is constant.

The 3 multifunctional prototypes underwent several analyses:

Kinematic and Finite Element Analysis

Kinematic and finite element analyses were performed on the 2 mechanical linkage designs (Prototypes 1 and 2), using Working Model (Knowledge Revolution, San Mateo, CA) software. Finite element analysis (FEA) was performed on the compliant scissors-grasper end-effector design (Prototype 3), using Pro/Mechanica (PTC, Needham, MA).

Bench-top Testing

Simple bench-top tests, grasping force at the jaws, cutting force at the jaws, and pull-off force were performed on the prototypes to quantify and compare force-deflection performance. For prototypes 1 and 2, grasping force was measured by closing the grasping jaws against a 500g Omega load cell, and for prototype 3, a Chatillon Model DFM 10-lb digital force meter was used. Cutting force in all cases was measured by closing the cutting jaws against a digital force meter. The measured cutting force was simply the closing force of the scissor jaw, and not a measure of the shear force between the scissor blades. Pull-off force was measured by gripping a 0.24 in section

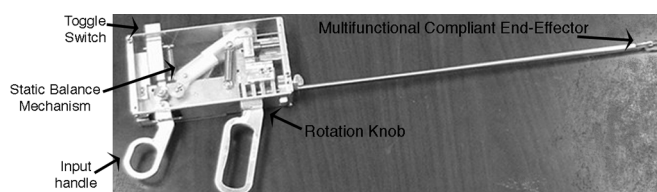


Figure 6. Prototype 3: Compliant Scissors-Grasper.

of red rubber tubing in the grasper jaws and measuring the force required to pull the tube from the jaws with a digital force meter. For comparison purposes, force measurements were taken for the Auto Suture Endo Dissect disposable instrument (US Surgical, Norwalk, CT). **Figure 7** shows the test set-up used to measure the cutting and grasping force of the mechanical linkage prototypes (left) and compliant prototype (right).

Rosser Station Evaluation/Dexterity Testing

The prototypes were tested in a basic bench-top laparoscopic training box. The Bean Drop and Cobra Rope Rosser station tasks, paper cutting, and “fuzzy ball” tests were used to assess dexterity (**Figure 8**).¹³ The fuzzy ball test was used to determine fine grasping accuracy of the “fuzz” with the tips of the instrument only. This test consists of picking up and passing several small soft plush balls back-and-forth between the prototypes and a disposable grasping tool for comparison (Endo Dissect, US Surgical, Norwalk, CT). For the paper-cutting test, the disposable grasping tool held a small piece of paper while

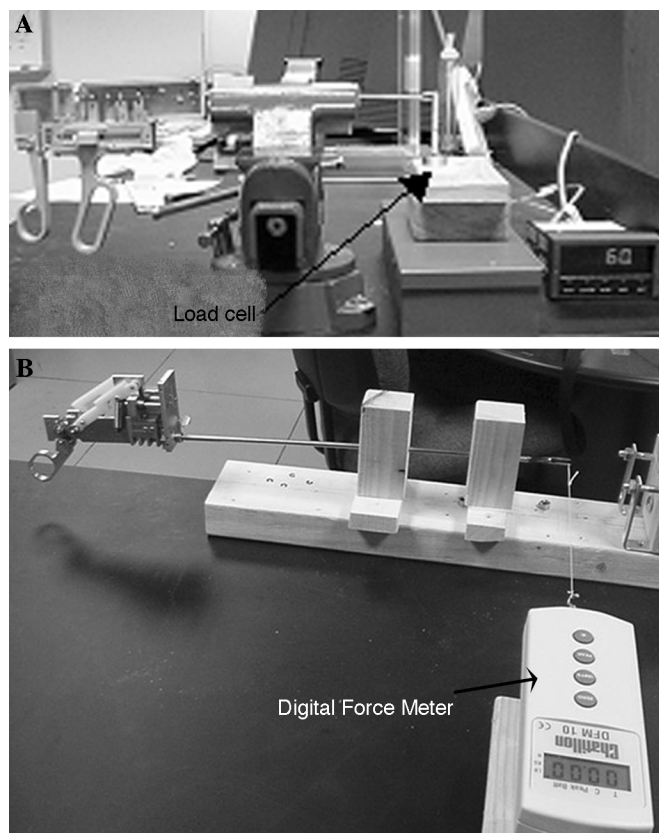


Figure 7. Bench-top Testing Set-up.

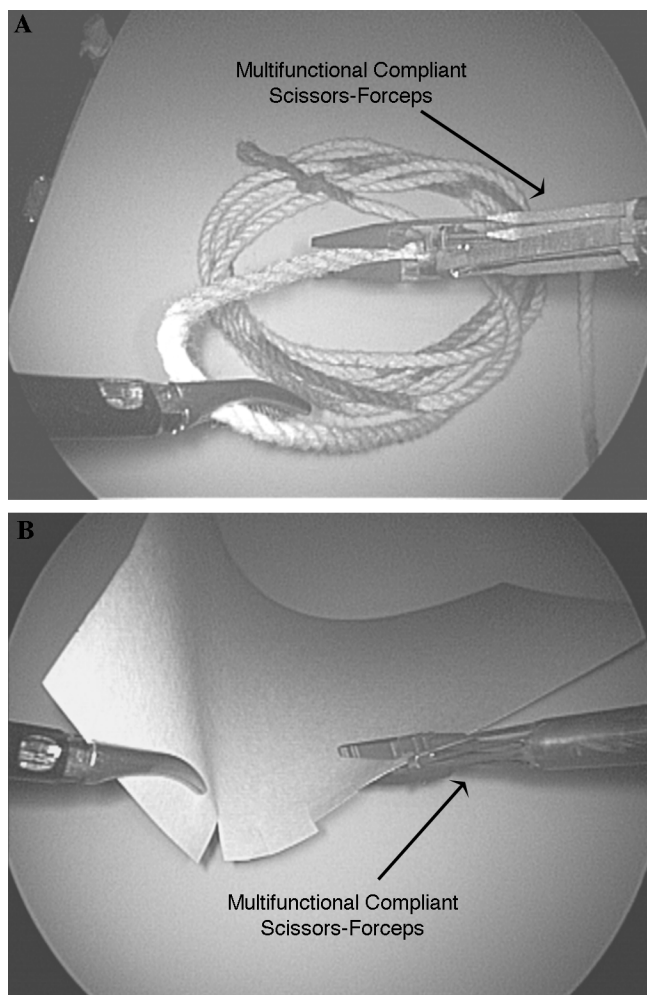


Figure 8. Box testing. Cobra Rope Test (A), Paper Cutting Test (B).

the multifunctional scissors was used (**Figure 8B**). The ease of toggling between instrument functions was also assessed during this procedure.

RESULTS

Kinematic and Finite Element Analysis

The mechanical grasper-scissors (Prototype 1) required 15° rotational input at the handle to produce 60° opening of the scissor jaws, and 6° of input handle rotation to produce 60° opening of the grasper jaws. For the mechanical grasper-scissors-articulator (Prototype 2), the grasper jaws opened approximately 60° for 10° of input handle rotation. The scissor jaw opened approximately 50° for 6° of input handle rotation. The articulation angle is inde-

Table 1.
Bench-top Testing Results

Measured Forces	Scissors-Grasper (Prototype 1)	Scissor-Grasper Articulator (Prototype 2)	Compliant Scissors-Grasper (Prototype 3)	AutoSuture Endo-Dissect*
Grasping	5.96 N (1.34 lb)	4.89 N (1.1 lb)	1.78 N (0.4 lb)	8.9 N (1.99 lb)
Cutting	8.9 N (2.0 lb)	6.23 N (1.4 lb)	0.36 N (0.08 lb)	N/A
Pull-off	11.1 N (2.5 lb)	10.2 N (2.3 lb)	1.51 N (0.34 lb)	14.2 N (3.17 lb)

*Tyco Healthcare, US Surgical Corporation, Norwalk, CT.

pendent of the input handle movement; sliding the articulation switch 12mm articulates the jaws 80°.

Finite element analysis (FEA) was performed on the compliant scissors-grasper (Prototype 3). Previously published results of the FEA^{11,12} indicate that a large deformation analysis predicts that the compliant mechanism acts very nearly like a linear spring with stiffness of approximately 140 N/mm (scissors) and 60 N/mm (grasper). Forces of 32.5 N and 17.5 N in the actuation pushrods are necessary to actuate the scissors and grasper, respectively. Using the static balance mechanism in the handle, the required forces and rotations at the input handle are approximately 7.84 N through 12° to close the grasping jaws and 8.74 N through 4.5° to close the cutting jaws. The maximum predicted von Mises stress is approximately 700 MPa in grasping and 800 MPa in cutting, compared with the yield stress of 1030 MPa for this material. Buckling analysis was also performed, and the results were acceptable with a buckling load factor of 2.0 in cutting and 4.1 in grasping.

Bench-Top Testing

The results of the simple bench-top tests (grasping force at the jaws, cutting force at the jaws, and pull-off force) are shown in **Table 1**.

Rosser Station Evaluation/Dexterity Testing

Table 2 shows a summary of subjective assessment of the multifunctional prototypes by 2 experienced laparoscopic surgeons during a single trial. Each performance parameter was scored on a scale from 1 to 5 with a score of 5 indicating optimal instrument function and performance.

DISCUSSION

The measured forces for Prototype 1 (Scissor-Grasper) and Prototype 2 (Scissor-Grasper-Articulator) were very similar, with the scissors-grasper prototype having slightly higher force capabilities. Prototype 3, the compliant scis-

Table 2.
Qualitative Assessment of Multifunctional Prototypes
(Scored on a Scale 1 to 5 With a Score of 5 Indicating Optimal Instrument Function and Performance)

Task	Scissors-Grasper (Prototype 1)	Scissor-Grasper-Articulator (Prototype 2)	Compliant Scissors-Grasper (Prototype 3)
Cobra	3	4	4
Bean Into Jar	3	4	3
Fuzzy Ball	3	4	4
Cut Paper	2	3	2
Toggle Between Functions	2	3	2
Usefulness of Dimensions*	5	5	5
Apparent Durability of Prototype	4	4	4
Articulated angle function	N/A	5	N/A

*Jaw length, jaw opening, etc.

sors-grasper, produced lower forces than the other 2 due to its inherent compliance. However, this prototype provided end-effector movement comparable to that of the mechanical linkage designs. The potential benefits of compliant tool end-effectors include ease of manufacture and assembly, ease of cleaning and sterilization due to lack of multiple millimeter-scale components, ability for actuation by mechanisms other than pushrods, and the potential for miniature or micro-scale end-effector designs due to their monolithic construction.

All prototypes were felt to have good durability and would withstand reasonable forces of port insertion and tissue manipulation within the abdominal cavity. All were noted to have excellent end-effector dimensions, comparable to that of existing laparoscopic instruments, and jaw lengths and openings that would be useful for basic laparoscopic tissue manipulation. The articulating function of Prototype 2 was noted to be excellent. This function allowed an instrument with the dimensions of a straight 5-mm dissector to have the nearly right angle reach of a much larger diameter instrument. All instruments performed in the good to fair range when performing the tests of basic dexterity. Paper cutting performance was somewhat below the performance of commercially available disposable instruments. The ability to rapidly toggle between functions was cumbersome and somewhat difficult.

CONCLUSIONS

The concept of multifunctionality for laparoscopic surgical instruments has been proposed. Three implementations of multifunctional instruments were designed, fabricated, analyzed, and subjectively evaluated. Multifunctionality was achieved by unique mechanical designs of the tool tip and handle, while maintaining similar operation to that of commercially available laparoscopic instruments. One drawback of the mechanical linkage designs (Prototypes 1 and 2) was that as multifunctionality increases, so does the complexity of the instrument designs, particularly in the tool tip and handle mechanisms. This creates a trade-off between instrument versatility and design simplicity. As more functions are incorporated and as smaller devices are considered, assembly and re-sterilization difficulties increase.

The subjective evaluations of the 3 prototypes demonstrated excellent apparent dimensions of the tool tips, but test of fine dexterity, cutting, and changing between functions were noted to be below what would be expected of standard disposable laparoscopic instruments. Most of the

shortcomings in the early prototypes can be attributed to inadequate fabrication tolerances at key points in the multifunctional jaw assembly. This was most notable in the cutting function due to the requirement for a precision mesh of cutting surfaces. The inadequacy of the toggle function is directly related to the handle design efficiency. It is anticipated that in future prototypes, a number of these noted deficiencies would be improved.

Although all 3 of these designs are in their first-round prototyping phase of development, the multifunctional instrument concept had been demonstrated. The Rosser station tests were useful in evaluating the instruments. Overall, the best performance in these tests was from Prototype 1 (scissors-grasper). Through further development, these designs will be refined, simplified, and improved to a point where they are directly useable and may be useful as surgical instruments.

References:

1. Melzer A. Endoscopic instruments: conventional and intelligent. In: Tooli J, Gossot D, Hunter JG, eds. *Endosurgery*. New York, NY: Churchill Livingstone; 1996:69–95.
2. Mehta NY, Haluck RS, Frecker MI, Snyder AJ. Sequence and task analysis of instrument use in common laparoscopic procedures. *Surg Endosc*. 2002;16:280–285.
3. Cohn MB, Crawford LS, Wendlandt JM, Sastry SS. Surgical applications of milli-robots. *J Robot Sys*. 1995;12:401–416.
4. Sastry SS, Cohn M, Tendick F. Milli-robotics for remote, minimally invasive surgery. *Robot Auton Syst*. 1997;21:305–316.
5. Pietrabissa A, Dario P, Ferrari M, et al. Grasping and dissecting instrument for hand-assisted laparoscopic surgery: development and early clinical experience. *Surg Endosc*. 2002;16:1332–1335.
6. Balazs M, Feussner H, Hirzinger G, Omote K, Ungeheuer A. A new tool for minor access surgery. *IEEE Eng Med Biol*. 1998;17:45–48.
7. Kolesa MS, Aranyi E, Kappel GS, inventors; United States Surgical Corporation (Norwalk, CT), assignee. Endoscopic surgical apparatus with rotational lock. US patent 5 609 601. March 11, 1997.
8. Yoon I, inventor; Yoon I, assignee. Surgical instrument with jaws and movable internal scissors and method for use thereof. US patent 5 984 938. November 16, 1999.
9. Oren R, Moor D, inventors; T.A.G. Medical Products Ltd. (Kibbutz Gaaton, IL), assignee. Surgical instruments for operating on joints. US patent 6 102 925. August 15, 2000.
10. Bacher U, inventor; Karl Storz GmbH & Co. KG (DE), as-

signee. Handle for a medical device. US patent 6 299 625. October 9, 2001.

11. Frecker MI, Dziedzic RD, Haluck RS. Design of multifunctional compliant mechanisms for minimally invasive surgery. *Minim Invasiv Ther*. 2002;11:311–319.

12. Dziedzic R. A *Design Methodology for Multifunctional Compliant Mechanisms with Application to Minimally Invasive Sur-*

gical Tool Design [master's thesis]. University Park (PA): University Park, PA: Penn State University; 2002.

13. Rosser JC, Rosser LE, Savalgi RS. Skill acquisition and assessment for laparoscopic surgery. *Arch Surg*. 1997;132:200–204.